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# Assessing the impact of demand response on peak demand in a developing country: The case of Ghana

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**Abstract.** Peak demand on electricity grids is a growing problem that increases costs and risks to supply security. Residential sector loads often contribute significantly to seasonal and daily peak demand. Demand response refers to consumer actions that change the utility load profile in a way that reduces costs or improves grid security by applying price signals and automated load shedding technologies. The methodologies that are used to achieve demand response can hardly be applicable in developing countries. Peak pricing of electricity, for instance, can hardly be implemented in many developing countries as high prices would disproportionately affect the many low-income households who do not have the capacity to take action to avoid paying high peak prices. This study aims to develop demand response methodology that can be applied in developing countries to achieve residential peak demand reduction. We use a consumer preference survey to develop a methodology suitable for developing countries. The method of diversified demand is used with energy audit and monitored data to estimate the potential peak load reduction and its cost-effectiveness for Ghana. Results show that peak reduction of 15-210 MW is expected by 2040 with a positive return on investment of 2-22% for all designed scenarios.

## 1. Introduction

The “commodity” electricity is prime in socio-economic transformation and a catalyst for improving the quality of life of citizenry in modern societies. Electricity enhances access and delivery of quality education, health services, agriculture modernisation, environmental sustainability, etc. The recently developed Sustainable Development Goals (SDGs) stressed the role energy had to play in the context of global human development. The target of SDG 7 is to scale up infrastructure and advance technology in the delivery of modern and sustainable energy services for all in especially developing countries [1]. SDG 7 is supposed to facilitate the execution of the “Sustainable Energy for All (SEforAll)” agenda which is a blueprint being pursued by many developing countries because of the pervasiveness of electricity supply constraints. Many of these countries are confronted with limited access to adequate, reliable and affordable electricity supply. In sub-Saharan Africa alone, a population of more than 590 million is without access to electricity and modern energy, making it the most electricity-poor region in the world [2]. Erratic power cuts and perennial power rationing, not for days but for months and even years, are two engrained symptoms. Unfortunately, Ghana has both in addition to over 7 million people



with access to electricity [3]. Since 1990, about four major power rationing has occurred, 1993/94, 1997/98, 2006/07 and the recent one which lasted for close to 4 years, 2012-2016 [4]. These supply challenges have largely been linked to inadequate electricity supply capacity and fuel supply constraints [4].

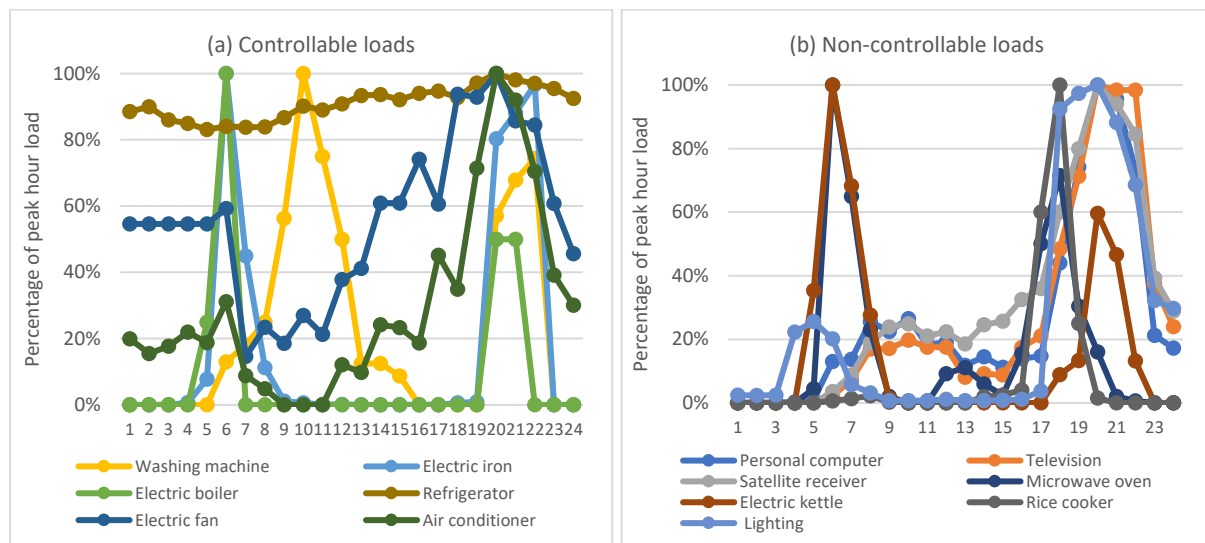
Although the present generation capacity seems adequate, high electricity price, grid instability and supply unreliability persist. In the future, supply dynamics might change because of demand growth uncertainties, fossil fuel price volatilities and climate change considerations. Demand response as part of demand side management strategies is a low hanging fruit that can provide some respite in balancing demand and supply without necessarily building more new generation capacities. Demand response is a set of actions intended to influence consumers to shift or curtail their energy use in response to price or incentive signals from the utility providers especially when network stability is under threat. These actions can change the time pattern and magnitude of the network load, thereby resulting in the desired load shapes [5]. Demand response has the potential to induce cost savings, blackout prevention or responsibility sensing [6–8]. A lot of studies in the extant literature have focused on price-based demand response with emphasis on behavior change induced by dynamic electricity pricing. Interestingly, most of the places with electricity supply challenges where demand response could be implemented do not have a smart grid, metering and communication infrastructure to support time-of-use tariff. Indeed, flat rate tariff regime is more pronounced. Moreover, majority of the households are low-income earners who use less electricity to meet common energy service needs like lighting. High peak prices might disproportionately affect them thereby derailing the essence of public good. Further, some households may lack the capability to understand and to respond to the price signal (e.g. may not understand the pricing system due to education limitations).

This study, therefore, aims to develop demand response methodology that can be applied in developing countries to achieve residential peak electricity demand reduction. The study uses a consumer preference survey conducted for Ghana to come up with a demand response deployment methodology for developing countries. The diversified demand modelling method along with energy audit and monitoring data is used to estimate the potential peak load reduction while Return on Investment (ROI) metric is used to assess its economic cost-effectiveness. The rest of the study is discussed in the next 3 sections.

## 2. Methods and data

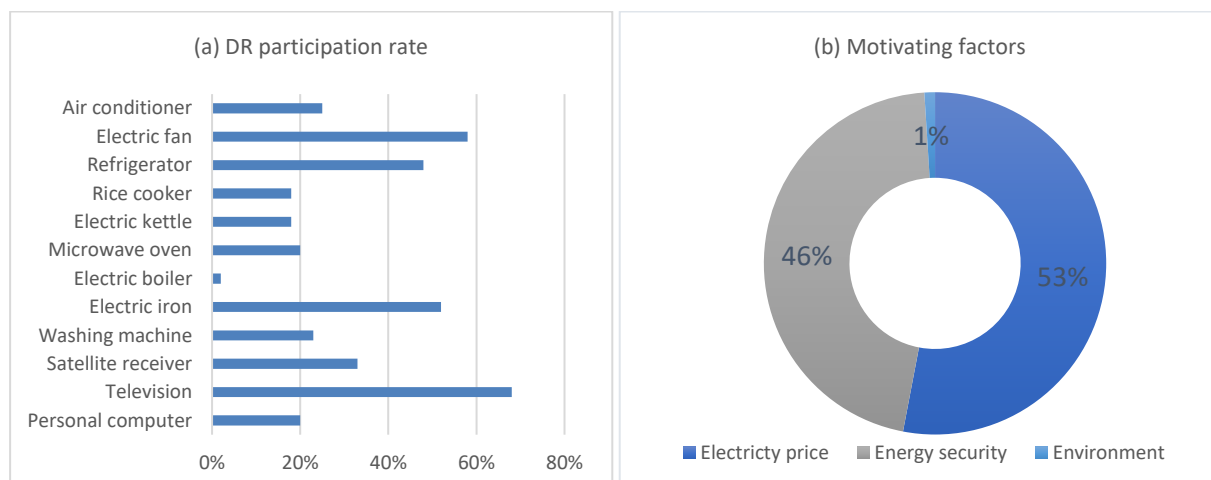
### 2.1. Appliance metering and voluntary demand questionnaire

The electricity consumption data of mostly used appliances are measured from 80 heterogeneous households in Ghana with different socioeconomic and energy use activity characteristics from February to July, 2018. A total of 12 appliances including television, personal computer, electric iron, satellite receiver, electric boiler, washing machine, electric kettle, refrigerator, rice cooker, electric fan, air microwave oven, air conditioner and lighting were measured. Four measuring instruments were used including the lamp meter, serial wattmeter, the energy detective device (TED) and power analyser data logger. The instruments were pre-calibrated to ensure accuracy of the measured data. The measured data were recorded within a time resolution of half an hour. The secured data of each appliance was aggregated and averaged for every hour to generate the hourly load variation curve. The load variation factors used were determined by dividing the average load for each hour by the peak load. The load profile for the appliances is presented in Figure 1 and categorized into controllable and non-controllable loads. The controllable loads are thermostatic or shiftable loads whose operation can be interrupted or postponed without energy service discomfort to the end user while the non-controllable are loads that can create energy service disruption to the end user.



**Figure 1.** Hourly load variation profile of measured appliances and lighting for (a) controllable and (b) non-controllable loads.

In addition to the appliance monitoring, energy audit information with voluntary demand response questionnaire was developed. This was to solicit responses from the representative members of the 80 households if they were willing to participate in demand response program and which motivating signals (price, energy security and environment) will inform their decision. Figure 2 shows the demand response participation rate for each appliance and the weight share of the motivating signals influencing their engagement for the representative households who indicated their participation willingness. Television, electric fan, refrigerator, electric iron had the highest demand response participation rate while electricity price and energy security signals had the highest in influencing their decisions.



**Figure 2.** (a) Demand response participation rate and (b) weight share of motivating factors.

## 2.2. Demand response modeling

A bottom-up approach based on an end-use model known as the method of diversified demand is used to estimate the daily load curve [9,10]. This method generates the total load profile of domestic household consumers which incorporates the activity and energy usage pattern of most predictable appliance loads [9]. The input parametric data needed for the model include the households' number,

appliance ownership, hourly variation factors, diversified household peak demand, demand response participation rate and the degree of demand response control for appliances.

To estimate the aggregated hourly demand pre-demand response event, Eq. (1) is used.

$$E_t^{BDR} = \sum_{a=1, \dots}^n MDD_t^a \times DRP^a + \sum_{a=1, \dots}^n MDD_t^a \times (1 - DRP^a) \quad (1)$$

where  $E_t^{BDR}$  is the total aggregate demand of domestic household consumers at any hour of the day before demand response event,  $MDD_t^a$  represents the maximum diversified demand of appliance  $a$  at any hour  $t$  of the day. This is calculated by multiplying the average diversified demand by the hourly variation factors of the appliance. The average diversified demand is estimated by multiplying the appliance stock (product of households' number and appliance ownership) and the diversified household peak demand (DHPD). The DHPD for appliance,  $a$  is the ratio of the coincident peak demand generated by that appliance to the number of households owning and operationalising it for service delivery.  $DRP^a$  is the demand response participation rate for appliance,  $a$  and it is simply expressed as the proportion of households willing to engage in the demand response activity.

The aggregate hourly demand after demand response action is calculated using Eq. (2).

$$E_t^{ADR} = \sum_{a=1, \dots}^n MDD_t^a \times DRP^a \times DRC_t^a + \sum_{a=1, \dots}^n MDD_t^a \times (1 - DRP^a) \quad (2)$$

where  $E_t^{ADR}$  is the total aggregate demand of domestic household consumers at any hour of the day after the demand response event.  $DRC_t^a$  represents the degree of control for a type of appliance that can be controlled without discomforting the user at specific time,  $t$  of the day.

The demand reduction delivered as a result of the demand response action at a specified time of the day can be estimated using Eq. (3).

$$\Delta E_t^{DRS} = E_t^{BDR} - E_t^{ADR} \quad (3)$$

where  $\Delta E_t^{DRS}$  is the demand reduction and it is expressed as the difference between the aggregate hourly demand before and after demand response action for a specific time,  $t$  of the day. The demand saved during the identified peak hour can be estimated.

### 2.3. Cost/benefit evaluation

To measure the cost-effectiveness of the demand response program, an economic indicator, return on investment (ROI) is used because of its simplicity and versatility. The ROI metric calculates the percentage increase or decrease in the return of an investment over a certain time frame. The ROI simply measures the profitability of an investment and it is expressed in Eq. (4). If investment's ROI is net positive, it indicates probable economic viability and a negative ROI implies a net loss.

$$ROI = \sum_i^n \left( \frac{DB - DC}{DC} \right) \quad (4)$$

Where  $DB$  is the discounted benefit,  $DC$  is the discounted cost,  $n$  is the lifetime/span of the demand response implementation and  $i$  is the project start time

### 2.4. Scenario and data assumptions

#### 2.4.1. Scenario definition.

Three scenarios consisting of demand shifting, thermostatic/interruptible (demand shaving) and combined (shifting plus shaving) were designed to assess the potential of residential households demand response (see Table 1 for the definitions).

**Table 1.** Scenario definition.

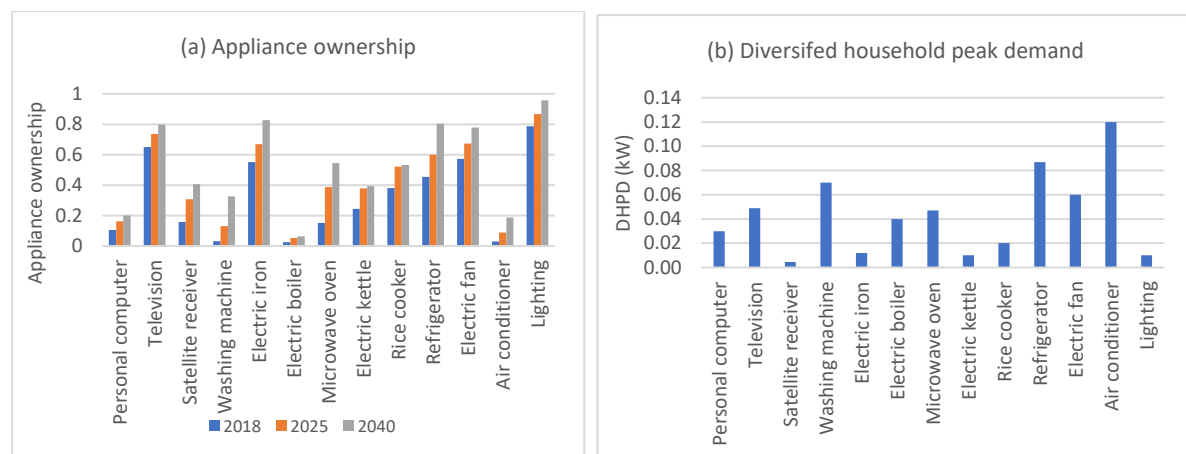
Scenario	Definition
Shifting (S1)	Coincidence demand of consumers is rescheduled to off-peak periods. Those appliances include washing machine and electric iron.
Thermostatic/interruptible (S2)	Coincidence demand of consumers is reduced through interruption and/or actuation of thermostatic loads (e.g. resetting of thermostat). The interruptible and thermostatic loads include refrigerator, air conditioner, electric boiler and electric fan
Combined (S3)	Shifting and shaving of load when there is a coincidence of consumers demand.

#### 2.4.2. Assumptions.

*Population, household size, appliance ownership, diversified household peak demand.* The households' number for a specific year is the population of that year divided by the household size (number of household inhabitants). The population and household size data was secured from reports of the Ghana Statistical Service [11–16], World bank [11–16] and the United Nations [11–16] and are presented in Table 2. The growth rate for population, household size and households' number for the period 2018–2040 is expected to be 1.74%, -0.31% and 2.05 respectively. The appliance ownership data is sourced from Diawuo et al. [4] and the diversified household peak demand (DHPD) is based on the appliance measurement data and are presented in Figure 3. The DHPD is assumed to be the same over the model time horizon.

**Table 2.** Household characteristics indicators [11–16].

Indicator	2018	2025	2040
Population	28,862,700	32,559,127	42,152,259
Household size	3.94	3.86	3.68
Households number	7,327,428	8,445,623	11,449,948



**Figure 3.** (a) Appliance ownership and (b) the diversified household peak demand for the period 2018–2040.

*Degree of control.* The controllable load is classified into shiftable and thermostatic/interruptible based on the mechanism of operation and pattern of usage. The flexibility in its control can result in load reduction. In this study, it is assumed that a thermostatic load reset during demand response event will deliver 25% reduction [17–19] in the peak hours of the appliance usage but the “snapback effect” during

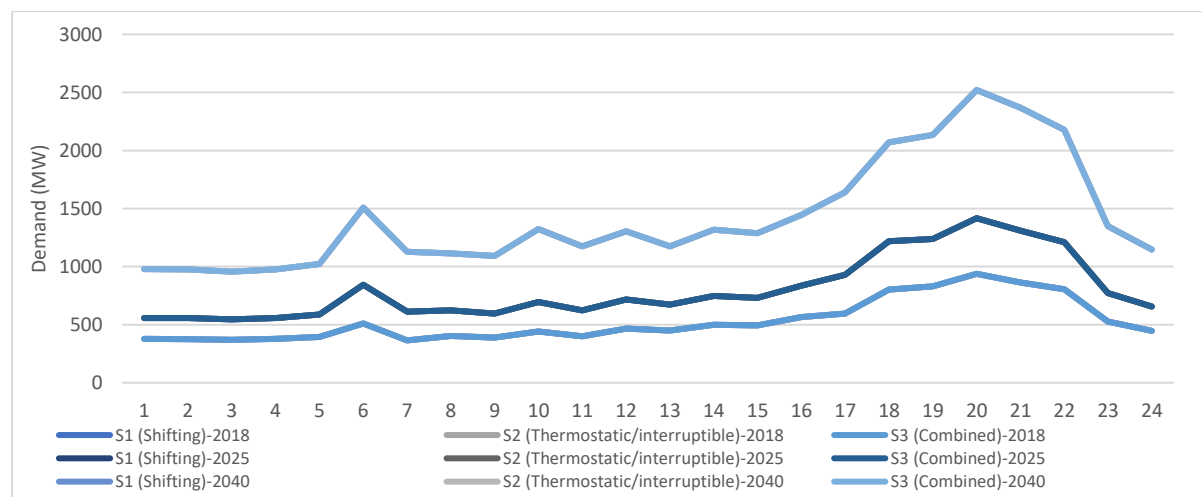
off-peak is assumed to be insignificant. In the load shifting, the energy remains unchanged because it is only transferred or postponed from peak hours to off-peak hours [17–19].

*Cost, benefit and discount rate data.* Monetary value is assigned to the costs and benefits in implementing the demand response. For the cost, S2 is assumed to cost US\$100 per consumer household [20] for investment in demand response control devices and communication architecture, S3 is assumed to be 101% of S2 cost to cater for similar items and an additional cost for educational campaign. S1 on shifting is assumed to be 2% of the cost of scenario 2 for being the cost related to educational campaign and administrative cost. The shifting will solely rely on consumer intelligence through information delivery and education. For the benefits (avoided cost), 3 elements are considered: avoided levelized capacity cost of 77 US\$/kW-yr [21–23], avoided levelized transmission & distribution cost of 86 US\$/kW-yr [21–23] and avoided emission cost of 10 US\$/tCO<sub>2</sub> [24]. A discount rate of 7.5% is used [25].

### 3. Results and discussion

#### 3.1. Load curves and peak demand reduction

For brevity, analysis of the results is presented for the period 2018, 2025 and 2040. The aggregate hourly demand before the demand response event as presented in Figure 4 shows an initial minimum peak at 6 am when most of the households are awake to commence preparation for their daily activities. The critical peak period occurs between 6-10 pm when they have returned from their daily activities and demand for certain energy services such as lighting, cooking, entertainment, etc. are required. The shape and pattern of the load is similar but with different magnitudes, principally due to the growth in the evolution of the appliance stock. In 2018, the hourly aggregate demand varied between 365-938 MW with the maximum peak occurring around 8 pm. By 2025, the hourly demand ranged from 546-1417 MW while in 2040 it varied from 957-2521 MW. The load curves before the demand response event for the scenarios in a specific year overlap.

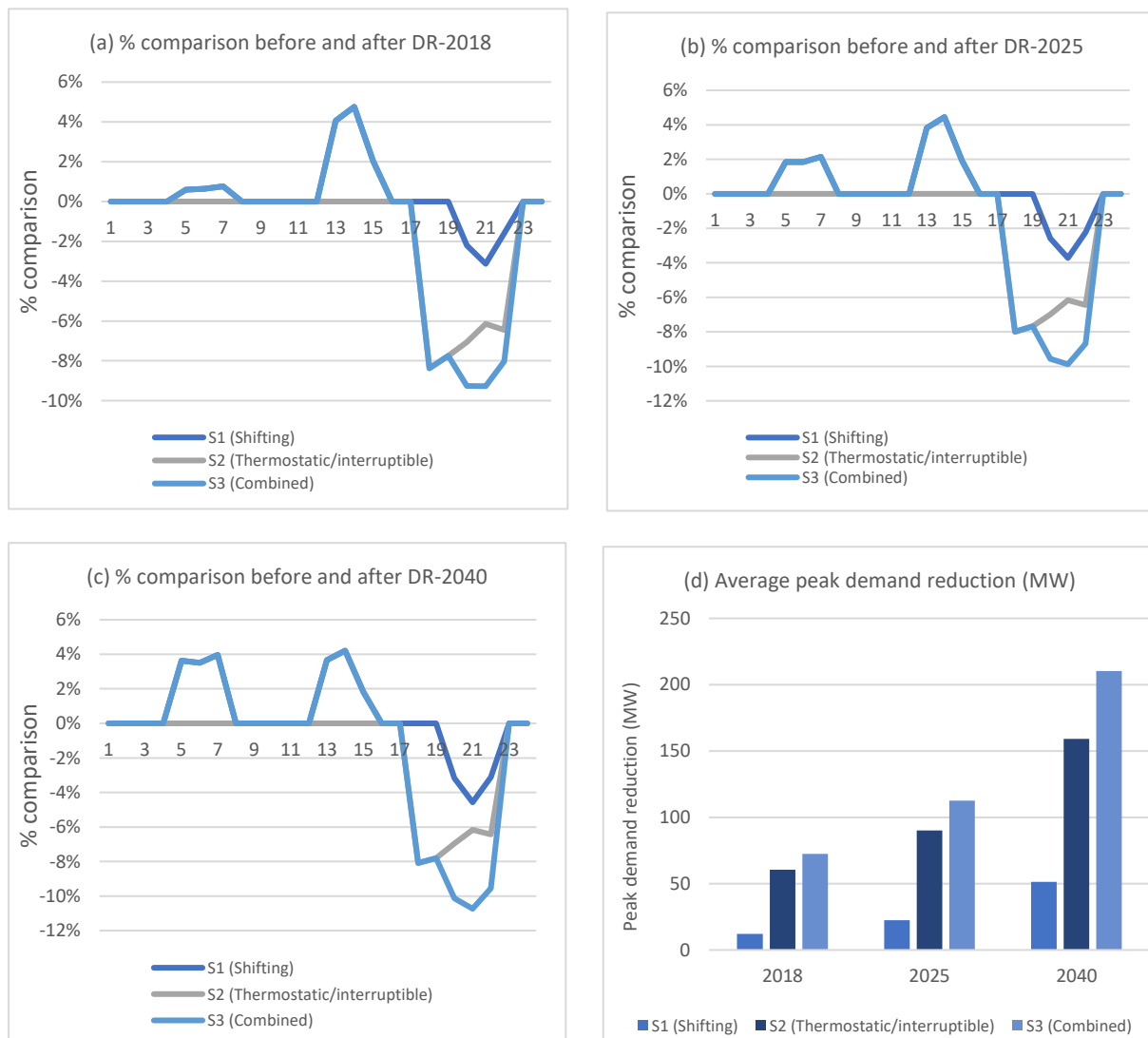


**Figure 4.** Estimated aggregate hourly demand curve for scenarios for a typical day in 2018 (bottom), 2025 (middle) and 2040 (top).

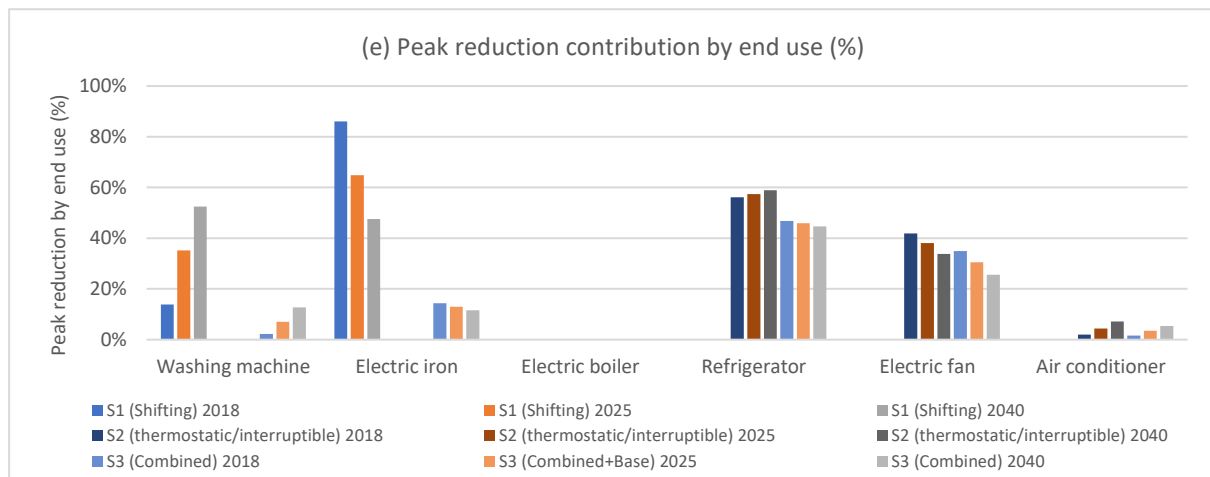
When the different demand response measures are applied as presented in Figure 5, the shifting scenario (S1) shows that comparison of the hourly demand curves before and after demand response varied between -5% to 5% for the all the years with a daily hourly average of 0%. The 0% is because, in demand shifting, the demanded energy remains the same but rather the coincidence load is rescheduled to an off-peak period. During the critical peak periods, an average reduction of 12 MW, 22 MW, 51 MW (representing 1-2%) was recorded for the period 2018, 2025 and 2040 respectively. The contribution of washing machine to the critical peak reduction was 14%, 35% and 52% while electric iron was 86%,



65% and 48% for the years 2018, 2025 and 2040 respectively. In the thermostatic/interruptible scenario (S2), the comparison between the hourly demand curves before and after demand response event showed a percentage variation of -8% to 0% and a daily hourly average of -1%. An average reduction of 60 MW, 90MW and 159 MW (representing an average of 7%) was recorded during the critical peak hours for the years 2018, 2025 and 2040 respectively. The weight share contribution of the thermostatic/interruptible appliances to the peak demand reduction is as follows; refrigerator (56%, 57%, 59%), electric fan (42%, 38%, 34%), air conditioner (2%, 4%, 7%) and electric boiler virtually 0% for the years 2018, 2025 and 2040 respectively. The low ownership of electric boiler is the main reason for its weight share. The combined scenario (S3) shows a relative comparative difference of -11 to 5% and a daily hourly average of -1% between the hourly demand curves before and after demand response event. An average critical peak reduction of 73 MW, 113 MW and 210 MW are recorded for the years 2018, 2025 and 2040 respectively. The contribution of appliances resulting in the reduction in the critical peak savings is as follows; washing machine (2%, 7%, 13%), electric iron (14%, 13%, 12%), refrigerator (47%, 46%, 45%), electric fan (35%, 30%, 26%), air conditioner (2%, 4%, 5%) and electric boiler virtually 0% for the years 2018, 2025 and 2040 respectively.





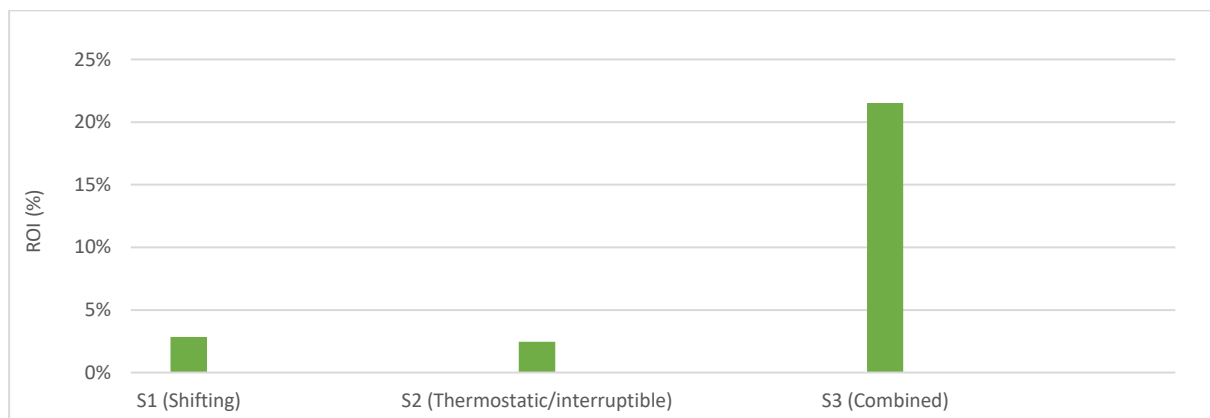


**Figure 5.** Comparison of demand curve before and after demand response for (a) 2018, (b) 2025, (c) 2040, (d) average daily peak demand reduction and (e) end use contribution to peak reduction

In summary, the study demonstrates that besides price signal, energy security and environment sensitivities could influence the behavior of consumers energy use. The results indicate a significant potential and opportunity for reducing residential peak demand. When the consumer is engaged and adequate information provided on electricity supply security constraints and energy decarbonization, then feedback can solicit an appeal for support in voluntary peak demand reduction. Incentive support through the provision of demand control devices and well-packaged schemes to encourage the purchase of smart appliances can inure to efficient use of energy and service delivery.

### 3.2. Financial analysis

The return on investment (ROI) for the time span between 2018 and 2040 shows a net positive for all scenarios indicating profitability if utility providers make an investment in supporting demand response programs. S3 had the highest ROI of 22% followed by S1 (3%) and S2 (2%) as shown in Figure 6. This implies that the benefits of the demand response exceed the cost after the model time span. This apparently suggests that the opportunity cost in investing in demand response programs is relatively far more than investing in peak technology plant. This has the potential to delay the construction of new generation capacity.



**Figure 6.** Return on investment on demand response implementation.

#### 4. Conclusion

Voluntary demand response has a strong role to play in securing future energy and decarbonisation. Despite the supply deficit in many developing countries, demand response opportunities are largely unexplored due limited information on consumer behaviour and lack of adequate economic analysis to assess its cost-effectiveness. This study combined consumer preference survey and household appliance monitoring data to assess residential demand response potential in Ghana. The findings demonstrate a substantial technical and economic potential of voluntary demand response. By 2040, an estimated critical peak reduction of between 15-210 MW is expected. Investment in demand response shows positive economic out-turn with a return on investment of 2-22% for a period of 2018-2040. The study confirms that aside price, energy security and environment signals have significant impact on energy usage behavior of consumers. This study provides more information and household load data to support decision-makers to develop regulatory, institutional, market-based and behavior centered policies tailored to conscientize and influence consumer energy use lifestyle. One limitation of this study is the use of the same hourly variation factors of appliances along time. This, however, can change based on pattern variations in consumer energy activities because of changes in income levels, lifestyle, etc. Future studies can incorporate stochastic tendencies in the appliance load profile. The impact of rebound effect due to consumers preference for bigger and high performing appliances could be tested in much detail.

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